Optical Experiments and Weak Interactions

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Recent optical experiments have demonstrated cases in which mirror symmetry in stable atoms is broken during absorption of light. These results, which are in contradiction with quantum electrodynamics, support the theory of unification of the electromagnetic and weak forces. The interpretation of these experimental results is based on exchanges of weak neutral Z^0 bosons between the electrons and the nucleus of the atom. The information obtained from low-energy experiments is different from, but complementary to, the results of high-energy experiments. Sensitive measurements in a simple, reliably computable atom are in quantitative agreement with the standard electroweak theory and put stringent constraints on alternative models. Attaining sufficient accuracy in the experiments and the computations for the electroweak radiative corrections to manifest themselves is now the challenge for experimenters and theorists.

LOOKING IN A MIRROR INTERCHANGES RIGHT AND LEFT handednesses. Many physical processes viewed in a mirror still obey the laws of the real physical world. Such processes are said to conserve parity. For so-called weak interactions (such as β decay), however, mirror symmetry is not preserved. Weak interactions, which thus exhibit right-left asymmetry, are said to violate parity (*1, 2*).

Recent optical experiments have demonstrated cases of a small parity violation in the absorption of light by atoms (*3*). Because light absorption is an electromagnetic process, it is traditionally expected to conserve parity. Therefore, parity violation in light absorption, however small it may be, is a striking phenomenon.

This discovery of parity violation in an atomic process was not unexpected. On the contrary, it was the outcome of many years of experimental effort. After the emergence of unified theories of the electromagnetic and weak forces—a revolution of physics in the early 1970's—numerous experiments were designed to test the new theories, to choose between them and to measure the fundamental constants involved. Searching for parity violation in the absorption of light was one of these experiments.

Observation of the extremely small parity-violation effects in atoms required not only much effort, but also special experimental conditions: the use of heavy atoms because of the rapid increase of the effects with atomic number and the choice of unusual atomic transitions. In a few cases, to prevent the tiny sought-for weak interaction from being entirely overwhelmed by the electromagnetic interaction, "highly forbidden" transitions were chosen. The absorption length of such faint transitions under real conditions is typically a million kilometers.

The parity-violating weak interaction does not produce a static electric dipole moment in the atom. Only during absorption or emission of light can the atom acquire an electric dipole moment that breaks mirror symmetry. This parity-violating transition dipole can be studied quantitatively by producing the transition in two experimental configurations that are right-handed and left-handed, symmetric with respect to some plane (mirror), and then measuring the right-left asymmetry as it affects some physical quantity in the final state. The most difficult step of the experiment consists of eliminating systematic effects by reducing instrumental imperfections of the handedness reversal.

Several investigators have observed right-left asymmetry in the absorption of light by heavy atoms (*3*). In cesium, for example, the asymmetry is now determined to 7% accuracy and is computed with an accuracy better than 5% owing to the simple (monovalent) structure of this atom (*4*). The agreement of experiment and theory provides a quantitative test of the standard electroweak theory—that is, the current unified theory of the electromagnetic and weak forces—in the case of the electron-nucleon interaction. Quantitative confirmation of mirror-symmetry breaking from low-energy experiments complements the results of high-energy experiments because of the huge difference in momentum transfer [typically 1 to 10 MeV/*c* in heavy atoms compared to 1 to 100 GeV/*c* in high-energy experiments (*c*, speed of light)]. The physics of these two energy ranges turns out to be different and to yield nearly orthogonal combinations of the two relevant fundamental constants, the so-called "weak charges" that characterize the weak interaction of the electron with the proton or the neutron. Experiments on parity violation in atoms thus put stringent constraints on alternative theories that have recently been proposed in the hope of extending unification to include the strong and gravitational forces.

Contradictions to Quantum Electrodynamics, But Support for Electroweak Unification

The standard electroweak theory is a generalization of quantum electrodynamics (QED), the quantum mechanical theory of electromagnetic interactions. The assumption of the existence of weak forces in stable atoms, with parity violation as a consequence, is an aspect of the electroweak theory not contained in QED. This is why parity violation in atoms has been sought for as a test of the electroweak theory.

QED is certainly the best established and most thoroughly checked physical theory. Countless experimental tests have been performed, always successfully; in some cases the agreement between experiment and theory is accurate to one part in 10^{11}. But in spite of this, the tiny parity violation observed in atoms is impossible

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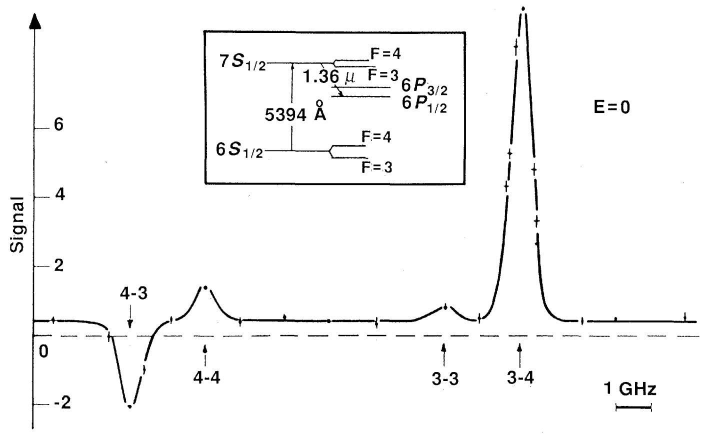


Fig. 1. Hyperfine structure of the highly forbidden $6S_{1/2}$–$7S_{1/2}$ transition observed without electric field. The incident beam is circularly polarized. The plotted signal is proportional to the electronic polarization of the $7S$ state (*18*). Inset: Energy levels of cesium involved in the parity-violation experiments (not to scale).

to accommodate in QED. This is not a matter of refining the computations or the measurements. The breaking of mirror symmetry is simply incompatible with the starting hypotheses of QED. Thus the very existence of parity violation in atoms attests to the need for an extended theory. In addition, there is considerable evidence that it manifests the weak electron-nucleon interaction predicted by the electroweak theory.

At the time of Fermi, testing for weak interactions in the absorption of light by atoms was out of the question for two major reasons. First, weak interactions were associated with disintegration processes (such as β decay or K capture), but no such process takes place in a stable atom. Second, weak interactions have extremely short range in comparison with atomic dimensions (about 10^7 times smaller). Thus neither quantitatively nor even qualitatively could it be imagined at that time how atomic properties might be perturbed by weak interactions.

It was in the early 1970's that the electroweak theory of Glashow, Weinberg, and Salam (*5*) was shown by 't Hooft (*6*) to be amenable to perturbative treatment mathematically consistent to any order. One essential prediction of this theory was the existence of weak interactions of a new type, which conserved the electric charge (as well as all internal quantum numbers) of each interacting particle. Such an interaction takes place between the electron and the nucleons (proton or neutron) of the atom. Unlike the weak interactions of β decay, this interaction can preserve the integrity of the atomic nucleus and is present in any stable atom.

The electroweak theory generalizes QED in the framework of the so-called gauge theories, in which the interaction between two particles occurs through exchange of "gauge bosons" of spin 1 (*6*). Electromagnetic interactions, for example, take place through exchange of photons, the most well-known gauge bosons. Because photons are electrically neutral, the charges (and natures) of the two interacting particles remain unchanged. Weak interactions of the new type also preserve the charges of the interacting particles, and the associated boson, called Z^0, is also neutral. Therefore these new weak interactions are classified as weak neutral current interactions.

It is well known that the exchange of a boson of mass M between two particles is associated with an interaction of characteristic range $\hbar/Mc$ between these particles. ($\hbar$, Planck's constant divided by 2π). Because the photon has zero mass, the electromagnetic interaction has infinite range. In view of the extremely short range of weak interactions, the Z^0 boson was predicted to be extremely massive. This was confirmed in 1983 after the discovery of the Z^0 in the proton-antiproton collider at the European Center for Nuclear Research (CERN). The Z^0 mass, about 100 times the proton mass, corresponds to a range of approximately 10^{-7} times typical atomic dimensions.

Like weak interactions of the type previously known, weak neutral current interactions were expected to violate parity, and therefore parity violation began to be expected in stable atoms as well. The extreme smallness of the estimated effects seemed prohibitive for experimental verification (*7*), but in 1973 the strength of parity-violating effects was predicted to increase slightly faster than the cube of the atomic number Z (*8*). The possibility of observing weak neutral currents in heavy atoms through mirror-symmetry breaking raised the hopes of investigators (*9*). Shortly after the start of the first atomic experiments, weak neutral currents were observed in neutrino experiments at CERN (*10*).

Mirror-Symmetry Breaking

As discussed above, parity conservation can be tested in an experiment in two handed configurations that are mirror images of one another. If the two results are also images of one another, then parity is conserved. Parity is violated to the extent that right-left asymmetry is measured.

In one class of experiments (*11–15*), parity violation was evidenced by a difference between the refractive indices for right and left circular polarization in the vicinity of suitable atomic transitions (*16*). The experiments were performed with linear polarization (that is, a coherent superposition of right and left circular polarization). The index difference was revealed through rotation of the polarization plane as a light beam propagated in an atomic vapor—an effect called spontaneous optical rotation of the vapor. The rotations observed in bismuth and lead were extremely small: about 10^{-7} rad for 1 m of dense atomic vapor. Therefore considerable effort was necessary to discriminate the genuine signal from spurious effects caused by optical defects (*3, 13, 17*).

In a second class of experiments, the right-left asymmetry was increased by combined use of several strategies. First, highly forbidden transitions, those whose (electromagnetic) amplitude is unusually small, were chosen. The contribution of the weak interaction, although still much smaller than the residual electromagnetic contribution, is in this way less severely overwhelmed. Transitions connecting the (populated) ground state to an excited state that differs only in the radial quantum number—for example, the $6S_{1/2}$–$7S_{1/2}$ transition of cesium and the $6P_{1/2}$–$7P_{1/2}$ transition of thallium—were particularly interesting (*8*). Here the two radial wave functions are orthogonal and the transition amplitude cancels in the first approximation, so that only small relativistic effects contribute. The $6S_{1/2}$–$7S_{1/2}$ transition of cesium, for example, is so weak that if the $7S$ state could decay through this transition only its lifetime would be 12 days. The lifetime is actually 50 nsec because decay takes place through other channels (Fig. 1, inset), so that the forbidden transition cannot be observed in emission. After several years of effort, it was observed by excitation of cesium vapor with an intense resonant laser beam, with subsequent detection of the fluorescent light emitted at a longer wavelength in the $7S$–$6P$ decay (Fig. 1, inset). This method, in conjunction with the use of polarized light for both excitation and detection, resulted in a specific signal well above noise and background (Fig. 1) (*18*).

A second advantage of using highly forbidden transitions is the possibility of utilizing the so-called Stark interference technique. Because the transition is so weak, a small d-c electric field (≃100 V/cm) is sufficient to induce a new transition amplitude that completely dominates the spontaneous amplitude. This Stark amplitude interferes with the tiny transition amplitude associated with the sought-for weak interaction. The interference term, which exhibits the parity violation of the weak interaction, is proportional to the applied electric field, whose magnitude and sign can be varied. This helps to distinguish the associated signal and to reject the detector noise. In these respects the Stark interference technique resembles heterodyne detection (*19*).

In practice, the right-left asymmetries observed in highly forbidden transitions can be 100 times those observed in optical rotation experiments (at the expense of longer integration times). This makes the former less vulnerable to systematic effects than the latter.

Several experiments in this class have been performed. The first two (*20, 21*), referred to as Stark–optical pumping experiments (*22*), were based on a similar concept. This consists of selecting the polarizations of both the resonant light that excites the transition and the fluorescent light monitored for detection. For instance, in the cesium experiment two circularly polarized, counterpropagating, resonant laser beams perpendicular to the electric field excite the atoms (Fig. 2). The mirror-symmetry breaking effect is manifested by partial circular polarization of the fluorescent light emitted in a direction perpendicular to both the beams and the field. That this breaks mirror symmetry is conspicuous in Fig. 2, which emphasizes the plane of symmetry in the experimental configuration and the breaking of this symmetry in the observed effect.

In the above experiments, the laser polarization and its direction with respect to the Stark field are the basic parameters of the configuration. By adding a magnetic field and altering the parameters, a wide range of Stark interference effects can be generated that manifest themselves through different mirror-symmetry breaking quantities. Two configurations have been investigated theoretically by our group (*23*), then experimentally by Drell and Commins in Berkeley, California (*24*), and by Wieman and colleagues in Boulder, Colorado (*25*). The first of these configurations can be described as handed absorption of linearly polarized light (Fig. 3a). The rate of absorption (and detected fluorescence) is different for right- and left-handedness of the coordinate system defined by the electric field **E**, the linear polarization $\boldsymbol{\epsilon}$ of the light, and the vector $(\boldsymbol{\epsilon}\cdot\mathbf{H})\mathbf{H}$. The second configuration can be described as circular dichroism in crossed **E** and **H** fields transverse to the beam (Fig. 3b). Circular dichroism is a difference in absorption rates for right and left circularly polarized light. Two configurations with incident right or left circular polarization are symmetric to one another with respect to a plane containing the light beam and the electric field. A difference in absorption rate (and subsequent fluorescence rate) evinces parity violation.

Right-Left Asymmetries: Mechanism and Size

In the presence of the weak interaction, the transition amplitude—which is squared to compute a transition probability—is the sum of two terms: the usual, purely electromagnetic amplitude A_{em}, and a new transition amplitude A_{w} involving a Z^0 boson exchange. Parity violation shows itself in the opposite behavior of A_{em} and of a part of A_{w} in the mirror image: one is odd, the other even (which one is which depends on the exact configuration). Thus in two experiments that are mirror images of one another, the transition probability takes on different values:

$$|A_{\mathrm{em}} \pm A_{\mathrm{w}}|^2 = (A_{\mathrm{em}}{}^2 + A_{\mathrm{w}}{}^2) \pm 2A_{\mathrm{em}}A_{\mathrm{w}} \qquad (1)$$

(For the sake of simplicity, A_{em} and A_{w} are assumed to be real, and the part of A_{w} that behaves like A_{em} in the mirror image is neglected.) The difference resides in the electroweak interference

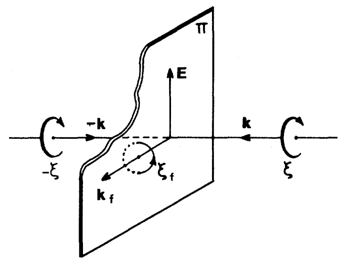


Fig. 2. Parity violation in Stark–optical pumping. **E** is the electric field and $\xi\mathbf{k}$ is the angular momentum of the incident counterpropagating photons. The symmetry of the experiment with respect to plane Π is broken by the result: a nonzero circular polarization ξ_f of the fluorescence photons emitted in a direction $\mathbf{k}_f$ normal to **E** and to the beams.

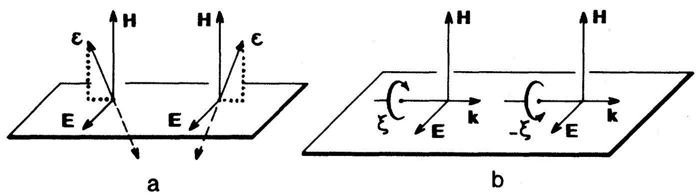


Fig. 3. Parity-violation experiments in crossed **E** and **H** fields. (a) Handed absorption of linearly polarized light. (b) Circular dichroism in fields normal to the beam. In both cases the two configurations symmetric with respect to a plane orthogonal to **H** are shown. They lead to different light absorption. **E** is a vector; **H** is axial; opposite directions of the polarization vector $\boldsymbol{\epsilon}$ are equivalent; ξ is the sign of the circular polarization.

term $\pm 2A_{\mathrm{em}}A_{\mathrm{w}}$. The amount of parity violation is characterized by the difference of the values of Eq. 1 normalized to their sum, a quantity known as the right-left asymmetry:

$$\begin{aligned} A_{\mathrm{RL}} &= 2A_{\mathrm{em}}A_{\mathrm{w}}/(A_{\mathrm{em}}{}^2 + A_{\mathrm{w}}{}^2) \\ &\cong 2A_{\mathrm{w}}/A_{\mathrm{em}} \qquad (\text{since } A_{\mathrm{w}} \ll A_{\mathrm{em}}) \end{aligned} \qquad (2)$$

This result is general. When parity violation occurs in the expression of a physical quantity, it does so through the appearance of a new contribution of opposite behavior in space reflection but of identical behavior in rotation, because the laws of all interactions are invariant in rotation. For example, a usually scalar quantity will give rise to a pseudoscalar contribution, and a usually axial quantity will give rise to a vector contribution.

The experiments discussed above are an illustration of these results. The fluorescence intensity (usually a scalar) contained a pseudoscalar contribution $(\boldsymbol{\epsilon}\cdot\mathbf{H})(\boldsymbol{\epsilon} \times \mathbf{H}\cdot\mathbf{E})$ in the experiment of handed absorption of linearly polarized light; in the case of circular dichroism in crossed fields it contained the pseudoscalar $\xi\mathbf{k} \times \mathbf{E}\cdot\mathbf{H}$ ($\xi = \pm 1$ is the pseudoscalar that represents the right or left helicity of the incident light, and **k** is its direction of propagation). In the experiment shown in Fig. 2, the angular momentum $\xi_f\mathbf{k}_f$ of the fluorescent photons contains a contribution of vector type as evidenced by its presence in the plane of symmetry.

The probability amplitude A associated with the exchange of a particle of mass M and momentum **q** can be shown, in a general way, to be proportional to $g^2/(M^2c^2 + q^2)$, where g is the coupling constant of the interaction. In the case of amplitude A_{w}, M is the Z^0 mass ($\sim$100 GeV/c^2); for amplitude A_{em} the photon mass is zero. Electroweak unification implies that the coupling constants of electromagnetic and weak interactions are comparable (*6*). The right-left asymmetry A_{RL} of Eq. 2 is thus

$$A_{\mathrm{RL}} \sim 2q^2/(M^2c^2 + q^2) \sim 2q^2/M^2c^2 \qquad (3)$$

(since the momenta q of Z^0 bosons exchanged in atoms are negligible compared with 100 GeV/c). This quadratic q-dependence indicates that low-energy experiments must overcome a serious handicap compared to high-energy experiments.

In the simplest atom, hydrogen, a typical value of q is $\hbar/a_0$, where a_0 (the Bohr radius) characterizes the atomic size. This leads to

$$A_{RL}(\text{hydrogen}) \sim 2\ [(\hbar/Mc)/a_0]^2 \sim 10^{-14} \qquad (4)$$

This minute value is directly related to the smallness of the weak interaction range $\hbar/Mc$ compared with the atomic dimension a_0.

As mentioned earlier, one way of drastically changing this situation is to use heavy atoms. Because of the very short range of the weak interaction, a valence electron "feels" the weak potential of the nucleus only when passing so close to the nucleus that the cloud of the other electrons no longer screens it from the nuclear Coulomb potential. In classical language, in an atom with Z protons the electron path close to the nucleus resembles the orbit in a hydrogenic ion of nuclear charge Ze. In such an ion the Bohr radius is a_0/Z instead of a_0. As a result, q^2 and consequently the asymmetry A_{RL} become Z^2 times larger. An additional factor Z originates in the proportionality of the weak interaction to the velocity of the electron near the nucleus, which in turn is proportional to Z. A more accurate calculation (*8*) predicts an enhancement of 10^6 or 10^7 when Z grows from 1 to 50 and 100. Combining this with the choice of a highly forbidden transition in a heavy atom leads to reasonable values for the expected right-left asymmetry of 10^{-5} in practice.

At this point the favored candidate for experiments is the $6P_{1/2}$–$7P_{1/2}$ transition of thallium ($Z = 81$) studied at Berkeley (*20, 24*). In choosing an element, however, one more criterion is important. Relating the measured quantity to the electroweak theory requires an atomic physics computation, and the need for reliability obviously favors atoms with a single valence electron, that is, the alkali metals. In view of the Z^3 increase, this explains the preference of our group for the stable alkali atom of highest Z, cesium ($Z = 55$). There is nevertheless considerable incentive for measuring effects in hydrogenic systems, where virtually no uncertainty would affect the theoretical interpretation (*26*). Several experiments with hydrogen and microwave radiation are in progress (*3*).

A Parity-Violating Transition Dipole

The laws of electromagnetic interactions are invariant in space reflection. This implies (in the absence of weak interactions) that atomic eigenstates have a defined parity: either +1 or −1. Their wavefunctions are either even or odd. Electric and magnetic dipoles, however, show opposite behavior in space reflection: the former is a vector, the latter a pseudovector. From these properties there follows a strict selection rule for electromagnetic transitions in atoms. This parity selection rule (sometimes referred to as the Laporte rule) requires that the electric dipole transition amplitude vanish identically between two states of identical parity. This applies to the $6S$–$7S$ transition of cesium and to the $6P$–$7P$ transition of thallium.

The presence of a parity-violating weak interaction in the atomic Hamiltonian implies that the eigenstates no longer have a pure parity. The $6S$ and $7S$ states of cesium, for example, become contaminated by nP states of opposite parity and give rise to new, slightly different eigenstates $\widetilde{6S}$ and $\widetilde{7S}$. The electric dipole matrix element between these new states is small but not zero. The weak interaction thus shows up through breaking of the Laporte rule. The parity-violating electric dipole amplitude $E_1^{pv} = \langle\widetilde{6S}\tfrac{1}{2}|d_z|\widetilde{7S}\tfrac{1}{2}\rangle$ (where d_z denotes the component of the electric dipole operator along an arbitrary direction) is precisely the transition amplitude A_w that characterizes the importance of the weak interaction in the transition ($\sim 10^{-11} ea_0$ in cesium; $\sim 10^{-10}\ ea_0$ in thallium, lead, and bismuth).

Could this contamination also generate a static electric dipole moment in an atomic state? The answer is no because of another symmetry, called time-reversal invariance, that is satisfied by both electromagnetic interactions and weak neutral current interactions. This symmetry forbids a nonzero average electric dipole in any stationary, nondegenerate atomic state. More generally it also forbids handedness in the static distribution of the electronic charge around the nucleus, as well as modification of any static property of the atom placed in uniform d-c electric and magnetic fields. Consequently the atom does acquire a parity-violating electric dipole, but only when it is in a nonstationary state (that is, a superposition of stationary states), as occurs during absorption or emission processes. So far all parity-violation experiments performed in atoms involve the detection of such a parity-violating transition dipole, whose amplitude A_w determines the right-left asymmetry. In such experiments the atom-radiation interaction is essential. [Different—not necessarily optical—experiments test simultaneous breaking of time-reversal and mirror symmetries in atoms through the search for a static electric dipole moment (*27*).]

What plays the role of the electromagnetic amplitude A_{em}? This depends on what kind of transition is chosen. Only transitions between states of the same parity are of interest, precisely because the Laporte rule excludes an electric dipole of the usual amplitude ($\sim ea_0$). The amplitude A_{em} is usually either a magnetic dipole amplitude or a small electric dipole amplitude controlled by a Stark field. The first situation occurs in optical rotation experiments, performed in allowed magnetic dipole transitions. The second situation corresponds to Stark interference experiments in highly forbidden transitions. In this situation the induced transition dipole is proportional to the Stark field through a certain polarizability tensor characteristic of the transition and described by two coefficients α and β [the ratio $\alpha{:}\beta$ is accurately known from independent measurements (*3*)]. Whatever the mirror-symmetry breaking quantity, in all Stark interference experiments the parameter finally extracted from the right-left asymmetry is the ratio E_1^{pv}/β. Physically this ratio represents the field value (typically ~1 mV/cm) for which the parity-violating and Stark-induced transition amplitudes would be just equal.

Measurements: Control of Systematic Effects

Table 1 lists the most recent data obtained for bismuth, lead, thallium, and cesium. Initial discrepancies in optical rotation values in bismuth have now been reduced, but the theoretical interpretation for bismuth and lead remains difficult in view of the complex atomic structure (*28*). The experiments with cesium in Paris and Boulder and with thallium at Berkeley, even though the mirror symmetry–breaking quantities were different, were all Stark interference experiments that followed common principles in discriminating the parity-violation signal by its specific behavior through reversal of the experimental handedness. Basically, reflections with respect to various planes were successively performed by reversing some of the parameters that defined the configuration: laser polarization, Stark field, magnetic field, or detected polarization of light. There were considerable differences in the practical realization, however.

Paris, 1982–84. At the École Normale Supérieure, a Stark–optical pumping experiment (Fig. 4) was performed in cesium vapor (*21, 29*). The circular polarization of the $7S$–$6P_{1/2}$ photons (Fig. 1, inset) originates, through the conservation of angular momentum, in the electronic spin polarization of the $7S$ state. This polarization contains two contributions (Fig. 4b). The large contribution $\mathbf{P}_0$ ($\sim 8 \times 10^{-2}$), of purely electromagnetic origin, is created along the beam direction by transfer of angular momentum from the circularly polarized light beam to the atoms. The tiny contribution $\mathbf{P}^{pv}$

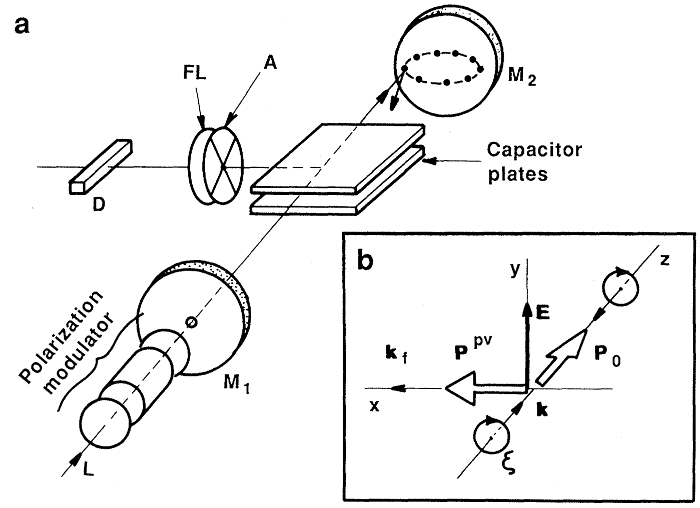


Fig. 4. The Paris experiment in cesium vapor: Stark–optical pumping. (a) The main elements of the apparatus. L, resonant continuous-wave laser beam; A, polarization analyzer; FL, filter and lenses; D, detector (for the $7S$–$6P_{1/2}$ fluorescence). Mirrors M_1 and M_2 inside the cesium cell allow approximately 60 forward-backward passages of the beam through the vapor (beam impacts schematized on mirror M_2), with a typical direction dispersion of less than about 1°. (b) Electronic polarization of the excited state. The component $\mathbf{P}^{pv}$ breaks mirror symmetry, while $\mathbf{P}_0$ preserves it (Fig. 2) (ratio $P^{pv}/P^0 \sim 10^{-5}$).

($\sim 10^{-6}$), which lies in the plane of symmetry of the configuration, breaks the mirror symmetry. Although angular momentum is usually axial, $\mathbf{P}^{pv}$ behaves as a vector in space reflection of the configuration because it reverses with the circular polarization of the beam (reflection in the $\mathbf{E},\mathbf{k}$ plane). It reverses also with the field $\mathbf{E}$ (180° rotation around the laser beam direction z). The right-left asymmetry is the ratio of the "abnormal" vector contribution to the "normal" axial one, $P^{pv}:P_0$ ($\sim 10^{-5}$ in a field of 100 V/cm). This ratio yields directly the quantity $E_1{}^{pv}/\beta$.

Polarization $\mathbf{P}_0$, orthogonal to the observation direction $\mathbf{k}_f$, is not detected. From time to time a magnetic field is applied along $\mathbf{E}$ to turn $\mathbf{P}_0$ (Hanle effect) so as to measure it. Comparison with the accurately known expected value provides absolute calibration of the apparatus (*30*).

There is considerable advantage in giving the experiment a plane of symmetry by using two counterpropagating beams. A single beam would give rise to an undesired additional parity-conserving polarization $\mathbf{P}_1$ colinear with $\mathbf{P}^{pv}$. With two counterpropagating beams, the effects, in principle, cancel each other. Since (axial) $\mathbf{P}_1$ is even when the circular polarization of the laser beam is reversed while (vector) $\mathbf{P}^{pv}$ is odd, residual $\mathbf{P}_1$ resulting from inexact cancellation can be distinguished from $\mathbf{P}^{pv}$.

Two measurements were made by means of the same arrangement in two different hyperfine structure components of the $6S$–$7S$ transition (Fig. 1, inset). In one case the electroweak interference that gives rise to $\mathbf{P}^{pv}$ involved the scalar component of the polarizability tensor (polarizability α); in the other case it involved its vector component (polarizability β). Since the measured physical quantities are different, the two experiments were independent.

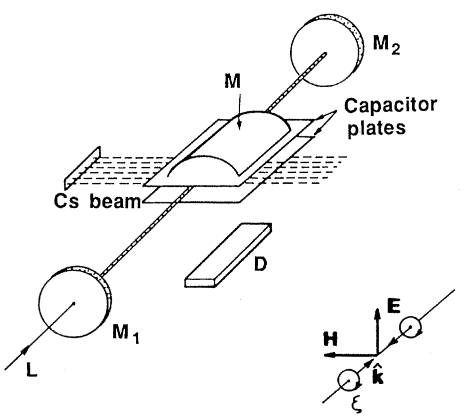
Boulder, 1985. In the experiment at the University of Colorado (*25*) (Fig. 5), parity violation appeared as a difference between the absorption of right and left circularly polarized light by cesium atoms placed in crossed d-c electric and magnetic fields transverse to the light beam. The effect involves the already mentioned pseudoscalar contribution $\xi\mathbf{k} \times \mathbf{E}\cdot\mathbf{H}$ in the absorption rate. The magnetic field $\mathbf{H}$ should be large enough for the Zeeman components to be resolved. As remarked by Wieman (*31*), Doppler broadening is reduced by using an atomic beam normal to the light beam: a field of 100 G then becomes sufficient to resolve the Zeeman structure. In addition, nearly all atoms of a beam are simultaneously in resonance with monochromatic light, in contrast to the situation with a vapor. This scheme offers much larger light collection efficiency than Stark–optical pumping because polarization analysis of the fluorescence becomes unnecessary and the required wavelength filtering much less severe. This leads to substantially higher counting rates and accordingly shorter integration times for the 1.5 times better statistical accuracy presently achieved.

The experiment consists of tuning the laser to resonance with one Zeeman component and then reversing the handedness of the configuration (ξ, $\mathbf{E}$, or $\mathbf{H}$). This reverses the parity-violating contribution to the fluorescence rate without affecting the dominant Stark-induced contribution. The ratio (typically 10^{-6} at E = 2500

Table 1. Results for parity-violating effects in atoms. Initial results with bismuth subsequently rejected or improved are not tabulated (*32*). All theoretical values refer to the transition, not to specific experiments. The theoretical values assume $Q_w = -112$, $\beta = 205\ a_0^3$ for thallium and $Q_w = -70.0$, $\beta = 27\ a_0^3$ for cesium.

Element	Location	Date	Optical rotation: $E_1{}^{pv}/M_1$ ($\times 10^8$)		Stark–optical pumping: $E_1{}^{pv}/\beta$ (mV/cm)	
			Experimental value*	Theoretical value*	Experimental value*	Theoretical value*
Bi (648 nm)	Novosibirsk	1979	-20.2 ± 2.7 (*11*)	-13 (*47*)		
	Oxford	1984	-9.3 ± 1.15 (*13*)	-17 (*48*)		
	Moscow	1984	-7.8 ± 1.8 (*15*)	-10.5 (*49*)		
Bi (876 nm)	Seattle	1981	-10.4 ± 1.7 (*12*)	-11 (*47*) -13 (*48*) -8 (*49*)		
Pb (1.28 μm)	Seattle	1983	-9.9 ± 2.5 (*14*)	-11 (*48*) -14 (*14*)		
Tl ($6P_{1/2}$–$7P_{1/2}$)	Berkeley (exp. 1)	1981			$-1.80\ ^{+0.65}_{-0.60}$ (*20*)	-1.31 (*50*) -2.17 (*40*)
	Berkeley (exp. 2)	1984			-1.73 ± 0.33 (*24*)	-1.88 (*40*) -1.80 (*40*)
Cs ($6S_{1/2}$–$7S_{1/2}$)	Paris	1982–83			-1.52 ± 0.18 (*29*)	-1.50 (*36*) -1.52 (*37*)
	Boulder	1985			-1.65 ± 0.13 (*25*)	-1.59 (*38*) -1.53 (*40*)

*Numbers in parentheses refer to the reference for the data.



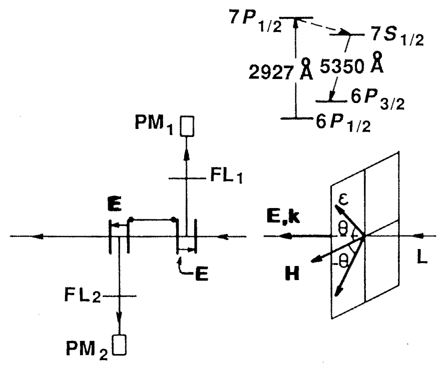


Fig. 5 (left). The Boulder experiment in an atomic cesium beam: circular dichroism in crossed **E** and **H** fields (sketch of the interaction region). L, resonant, circularly polarized continuous-wave laser beam; M_1 and M_2, spherical mirrors forming an interferometer; M, light collection mirror; D, detector (for the $6P_{1/2,3/2}$–$6S$ branch of the $7S$ decay). Fig. 6 (right). The Berkeley experiment in thallium vapor: handed absorption of linearly polarized light. There are two interaction regions with opposite electric fields. L, pulsed narrow-band laser beam; FL, filter and lenses; PM, photomultipliers detecting the $7S$–$6P_{3/2}$ cascade of the $7P_{1/2}$ decay.

V/cm) again yields E_1^{pv}/β. The dependence of the parity violating contribution on the Zeeman and hyperfine structure component yields further discrimination of the parity-violating signal.

Berkeley (experiment 2), 1984. Because thallium is heavier than cesium, the experiment at the University of California at Berkeley benefited from a roughly ten times larger E_1^{pv} amplitude. This compensated partially for the high temperature (1000 K) required when using thallium and the difficulty in operating the ultraviolet laser in the narrow band with high power (*24*).

The highly forbidden $6P_{1/2}$–$7P_{1/2}$ transition excited in thallium connects two states of same radial number, as in cesium. It is detected through the fluorescence emitted in a second step of the decay of the $7P_{1/2}$ state (Fig. 6). The parity-violating effect is handed absorption of plane-polarized light in crossed **E** and **H** fields, observed through the pseudoscalar contribution $(\boldsymbol{\epsilon}\cdot\mathbf{H})(\boldsymbol{\epsilon} \times \mathbf{E}\cdot\mathbf{H})$ in the fluorescence rate. It is odd with reversal of **E** or of the angle θ between $\boldsymbol{\epsilon}$ and **H** but even with reversal of **H**. It is also dependent on the laser frequency, with characteristic variations and sign changes. As in the Boulder experiment, the Zeeman components must be resolved, but a field of 3 kG is required because of Doppler broadening in the vapor. The choice of the beam direction along **E** (Fig. 6) can be shown to minimize spurious effects.

By performing handedness reversals, one can in principle extract E_1^{pv}/β from the ratio between the odd and even contributions to the fluorescence rate ($\sim 10^{-5}$ at $E = 100$ V/cm). A problem arises from d-c background, but this is circumvented by a detailed analysis of the line shape and by alternated measurements in two Zeeman components where the expected asymmetries are opposite (the angle $\theta = \pm 35°$ is selected so as to give these two components equal intensities).

In the practical realization of all parity-violation experiments in atoms, the central problem is that of systematic errors because nonrigorous reversal of the handedness makes large parity-conserving effects look partially parity-violating. The problematic history of atomic parity-violation experiments is proof that the array of checks and precautions discussed below is not excessive. Disagreement about the very existence of an effect in the first observations regarding optical rotation in bismuth (*11, 32*) has emphasized the need for undisputable results.

The method now in use requires that all imperfections that could generate false parity-violation signals be incorporated in a model. Separate measurements have shown atomic signals to be reliable, accurate probes of these imperfections (*33*). In the Paris experiments these signals were recorded throughout data acquisition. The uncertainty reported in the result includes not only the statistical uncertainty of these auxiliary measurements but also their own systematic imperfections (*29*). In addition, before the parity-violation measurements much effort was devoted to reducing all imperfections so as to keep each systematic error below 3% of the observed effect at any time. As a result, the net systematic correction is less than 2%. The Boulder group has reported a better final accuracy but after systematic corrections ranging from −50 to +50%, with a final average of 14% (*25*).

The reliability of the results of the Paris, Berkeley, and Boulder experiments (Table 1) was further ensured by consistency checks on the data, redundancy in the asymmetry measurements, and a thorough understanding of the wide range of purely electromagnetic effects exhibited by this unusual type of transition. While rendering overlooked systematic effects unlikely, the comprehension of all observed effects also provided numerous cross-checks. The agreement of the two measurements performed in Paris on two different electroweak interferences constitutes an additional cross-check, as does the agreement of the Paris and Boulder results (whose combination leads to 7% accuracy). The $6S$–$7S$ transition of cesium is so far the only case of unquestioned agreement between results obtained by independent groups using different experimental approaches.

Interpreting the Observed Parity Violation

Although Stark experiments provide the ratio E_1^{pv}/β of the parity-violating transition dipole to the transition polarizability β, so far most atomic computations predict only E_1^{pv}. Therefore, some determination of β is necessary. Even when a calculation of E_1^{pv}/β does exist, this is interesting as a test of the atomic theory. A semiempirical method of determining β for cesium was introduced by Hoffnagle and co-workers (*34*). It is based on the empirical knowledge of the Stark shifts and lifetimes of the $6P$, $7S$, and $7P$ states. Theoretical and empirical uncertainties together do not exceed 3% (*29*). In thallium, a direct empirical determination of β with 5% uncertainty has been achieved (*35*).

How large is the uncertainty introduced by the choice of an atomic model in the result of the calculation that predicts E_1^{pv} (*28*)? Among the elements where parity violation has been observed, only cesium has given rise to as complete and accurate a calculation as that of Dzuba and colleagues (*36*). Their calculation predicts energies, oscillator strengths, and hyperfine structure splittings of S and P states to an uncertainty of not more than a few percent. It starts from first principles, and many-body effects due to electron-electron interactions are incorporated in a self-consistent way. Its result concerning E_1^{pv} is confirmed by several independent, somewhat less complete calculations. Some of these calculations also start from first principles (*37*); others follow semiempirical approaches that introduce empirical data in the computations (*38*). Taking the average of all these consistent predictions, less than 5% uncertainty

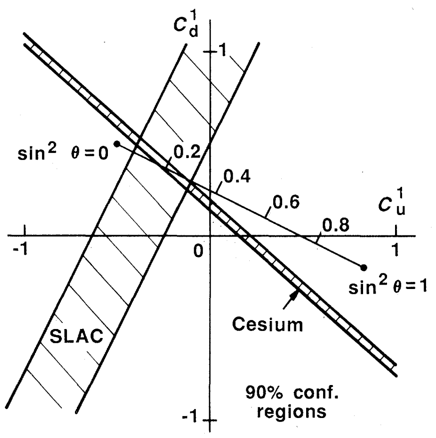


Fig. 7. Experimental, model-independent determination of the weak charges of the u and d quarks. The striped areas are the domains allowed by the high-energy SLAC experiment (*42*) and by the cesium experiments (*25, 29*). The graduated segment represents the predictions of the standard electroweak theory for values of the parameter $\sin^2\theta$ from 0 to 1.

associated with the atomic theory may be conservatively expected. Moreover, the parity-violating weak interaction between electrons, expected from the beginning to be small (*8*), has been confirmed as playing a negligible role for cesium (*39*). For thallium the situation is more difficult (*40*). In contrast with Cs^+, the Tl^+ ion does not have a simple rare gas structure.

Nuclear Weak Charge and Other Implications

In the parity-violating electron-nucleon interaction in heavy atoms, the Z^0 boson behaves like a heavy photon with respect to the nucleus. The parameter that plays the role of the electric charge of the nucleus is called the nuclear weak charge, Q_W. The measured parity-violating amplitude E_1^{pv} is the product of this weak charge and a purely atomic factor provided by the atomic calculations. Thus Q_W is precisely the electroweak parameter to which the experiments in heavy atoms are sensitive.

From the atomic theory predictions for cesium discussed above, the weighted average of the Paris and Boulder results yields -71.5 ± 5.8 as a current best empirical determination of the nuclear weak charge of cesium (experimental and atomic theoretical uncertainties combined quadratically). This result is in good agreement with the prediction of the standard electroweak model of -70.0 ± 0.9 [for $\sin^2\theta = 0.223 \pm 0.004$, radiative corrections included (*41*)].

Weak charge is conserved like electric charge. Independent of any electroweak model, the weak charge of the nucleus is consequently the sum of the weak charges of its constituents—that is, the Z protons and N neutrons, or equivalently the $2Z + N$ u quarks and $Z + 2N$ d quarks. These charges are directly related to the fundamental coupling constants C_u^1 and C_d^1 that characterize Z^0 exchange between a u or d quark and an electron.

Up to now, only one high-energy experiment has provided information concerning C_u^1 and C_d^1. This was the scattering of longitudinally polarized electrons performed at the Stanford Linear Accelerator (SLAC) at momentum transfer values of about 1 GeV/c (*42*). In this highly inelastic scattering, the nucleons are broken and the quarks act incoherently. In atoms, on the other hand, the nuclei remain intact and the quarks act coherently. Thus it is not surprising that the linear combinations of C_u^1 and C_d^1 extracted from the SLAC and atomic experiments are different. In practice, they turn out to be nearly orthogonal. Combining the results of both types of experiments allows both C_u^1 and C_d^1 to be determined; neither experiment can achieve this alone. This complementarity is illustrated in Fig. 7 for cesium.

Still more remarkable is the agreement of this model-independent interpretation with the prediction of the standard electroweak model. Each point of the graduated segment of Fig. 7 represents the prediction of the standard model for one value of its parameter $\sin^2\theta$. The intersection of the two experimentally allowed areas (striped) is consistent with the prediction of the standard model for $\sin^2\theta$ of approximately 0.23. This value, measured in Z^0 exchange between electron and nucleon, turns out to agree with values obtained at high energy for different partner pairs (Fig. 8) (*43*).

In view of the small angle between the striped area representing cesium and the graduated segment of Fig. 7, the cesium experiment is not suitable for an accurate determination of $\sin^2\theta$. Its test of the standard electroweak model, however, is to this same extent less dependent on the value of $\sin^2\theta$. If the striped area and the segment were parallel, $\sin^2\theta$ could not be determined at all, but there would be agreement or contradiction between the cesium experiment and the standard model irrespective of a value of $\sin^2\theta$.

Atomic experiments test the weak interactions at long distances not accessible to high-energy experiments. This is why they are sensitive to exotic weak interactions that elude the latter. They restrict alternative electroweak theories that assume additional neutral bosons by putting constraints on the masses of these bosons and on the vector or axial nature of their coupling to the electron and quarks. For example, they impose constraints on a hypothetical second neutral boson of mass 1 keV/c^2 to 1 GeV/c^2; no other experimental observation so far says anything concerning such a light boson (*44*).

Open Questions

There is considerable incentive to increase the accuracy of the determination of the right-left asymmetries in heavy atoms. A first goal is a precise determination of the nuclear weak charge. Radiative corrections of the electroweak theory amount to 6% in Q_W. They are of fundamental importance, like the Lamb shift or the anomalous magnetic moment of the electron in QED. Therefore, at an accuracy of a few percent the significance of a comparison between experiment and theory will acquire a new dimension. In addition, such determinations would make more stringent the constraints imposed by atomic results on the alternatives to the standard electroweak theory. This is presently of particular importance in view of the huge theoretical effort invested to unify electroweak interactions with strong and gravitational interactions.

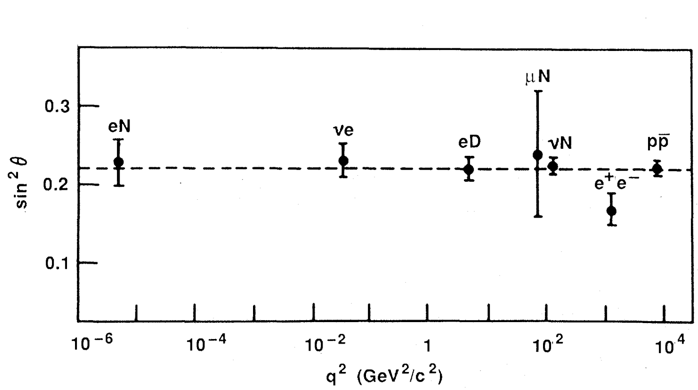


Fig. 8. Determination of $\sin^2\theta$ from cesium experiments and from scattering of various partners at much higher values of the momentum transfer q. N, nuclei; D, deuterons; p$\bar{p}$, the proton-antiproton scattering experiment at CERN that led to the discovery of the charged gauge bosons $W^{\pm}$. The dashed line represents the average of all data (*43*): $\sin^2\theta = 0.223 \pm 0.004$ (including radiative corrections). Error bars are estimated typical uncertainties, including both the root-mean-square statistical uncertainty and the typical systematic uncertainty.

A question fully open from an experimental point of view is that of the possible existence of a weak neutral current interaction involving the nucleon's spin. Such an interaction is theoretically predicted but still unobserved, even at high energy. It would involve axial coupling of the Z^0 boson to the nucleons (with new coupling constants C_p^2 and C_n^2) instead of vector coupling through the weak charges. The contributions of the various constituents would combine like spins instead of add like charges. The enhancement in heavy atoms then loses one factor Z, which explains why this interaction, if present at all, is dominated in heavy atoms by the contribution associated with the weak charges. Yet it does not seem impossible to test its existence. One line of attack consists in accurately comparing the parity-violating dipole amplitude relative to two hyperfine structure components of the same transition. If the components are chosen correctly, the uncertainty introduced by atomic calculations is eliminated in the ratio, which then yields the weak axial moment of the nucleus (*29*). A nuclear physics calculation is necessary, however, to interpret the moment in terms of C_p^2 and C_n^2, and this is an unavoidable source of large uncertainty. Consequently, in spite of their high interest, such measurements cannot be considered a substitute for experiments with hydrogen, which would directly yield the proton's axial coupling C_p^2 (*26*).

Wieman and colleagues are preparing a measurement of higher precision with cesium. In addition, various new detection schemes currently investigated in the 6*S*–7*S* cesium transition look promising. They aim at improving the detection efficiency of the 7*S* state. In one project 7*S* atoms are optically excited to a Rydberg state, then ionized and detected in a space-charge limited thermionic diode (*45*). A totally different approach consists in monitoring stimulated emission in the 7*S*–6*P* transition induced by a probe beam (*46*). The right-left asymmetry created in the 7*S* state will then show up in the dependence of the probe gain on the polarizations of the excitation and probe beams. Because all photons are emitted in the direction and at the frequency of the probe, high detection efficiency is expected. Moreover, in suitable configurations amplification of the right-left asymmetry itself can be expected as the probe beam propagates through the vapor.

Optics and weak interactions are two fields of physics that used to "ignore" each other, but common goals have built bridges between them. Optical experiments in heavy atoms have exciting new possibilities of probing further the mirror symmetry–breaking weak interaction between electron and nucleon. The still unexplored but accessible area of this research field appears to be sufficiently broad to maintain the enthusiasm of theorists and experimenters for many years.

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